CHAPTER 7

Planning a Celestial Tour

Space mission design aims to maximize science return within the constraints and limitations imposed by the laws of nature and the safe, reliable operation of the spacecraft. Major mission design variables that may influence science return from the Cassini–Huygens mission are design and selection of the interplanetary trajectory, design and selection of spacecraft orbits and the use of the spacecraft and instruments in making observations and returning data to Earth. This chapter discusses the role of planetary swingbys in achieving the Cassini–Huygens trajectory to Saturn, along with the spacecraft's activities during this time.

The Interplanetary Mission

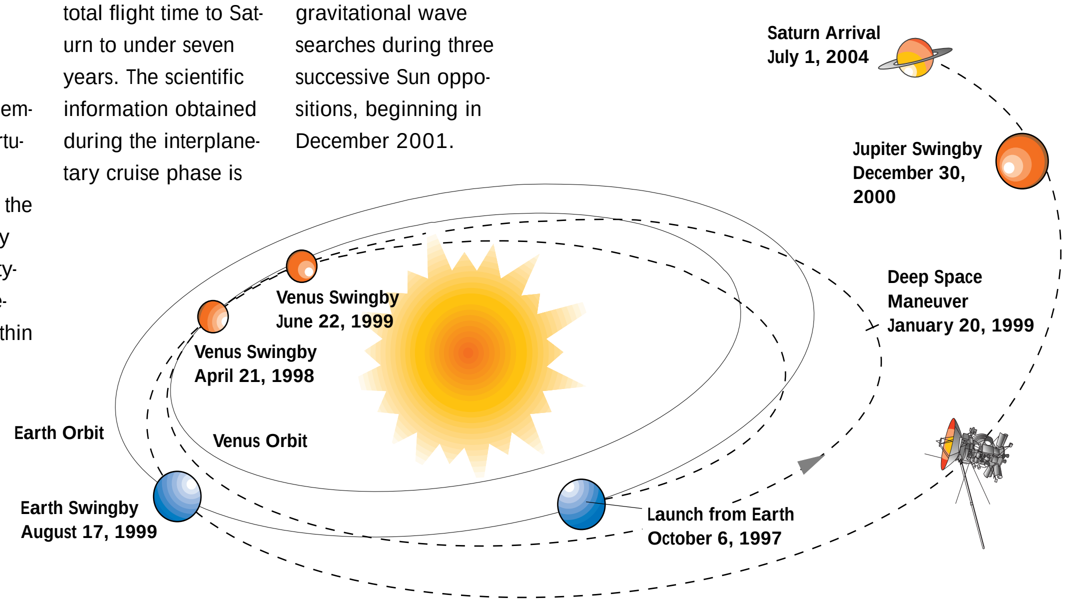
The Cassini–Huygens mission uses trajectories requiring planetary swingbys to achieve the necessary energy and orbit shaping to reach Saturn. The primary trajectory for Cassini is a Venus–Venus–Earth–Jupiter Gravity Assist (VVEJGA) transfer to Saturn.

As the name implies, the VVEJGA trajectory makes use of four gravity-assist planetary swingbys between launch from Earth and arrival at Saturn. The use of planetary gravity assists reduces launch energy requirements compared to other Earth–Saturn transfer modes, and allows the spacecraft to be launched by the Titan IVB / Centaur. Direct Earth–Saturn transfers with this launch vehicle are not possible for Cassini–Huygens.

The nominal launch period of the primary mission opens on October 6, 1997, and closes on November 4, 1997, providing a 30-day launch period. A contingency launch period is extended beyond the nominal launch period to November 15, 1997, to increase the chances of mission success — although possibly degrading to some extent the scientific accomplishments of the nominal mission. The

THE EASY WAY TO FLY

The Venus–Venus–Earth–Jupiter Gravity Assist (VVEJGA) trajectory that Cassini–Huygens will take requires a deep space maneuver between the two Venus swingbys. This maneuver reduces the spacecraft orbit perihelion (the closest point with respect to the Sun) and places it on the proper course to encounter Venus for a second time in June 1999. After the Earth swingby in August 1999, the Cassini–Huygens spacecraft will be on its way to the outer planets, flying by Jupiter in late December 2000. The fortuitous geometry of VVEJGA provides the unique opportunity of a double gravity-assist swingby, Venus 2 to Earth, within 56 days, reducing the total flight time to Saturn to under seven years. The scientific information obtained during the interplanetary cruise phase is limited primarily to gravitational wave searches during three successive Sun oppositions, beginning in December 2001.



opening and closing of the nominal launch period are chosen such that the launch vehicle's capabilities are not exceeded and the mission performance and operational requirements are met.

After launch, the trajectory is controlled through a series of trajectory correction maneuvers designed to correct errors in the planetary swingbys. Each planetary swingby has the effect of a large maneuver on the trajectory of the spacecraft. For the prime trajectory, the four swingbys can supply the equivalent of over 20 kilometers per second of Sun-relative speed gains — an amount not achievable using conventional spacecraft propulsion.

Typically, interplanetary swingbys are controlled using two approach maneuvers and one departure maneuver, with additional maneuvers added at critical points. About 20 maneuvers will be needed to deliver the spacecraft from launch to Saturn. The controllers' knowledge of the actual location of the spacecraft is obtained using measurements made from the Deep Space Network. This system of maneuvers is capable of delivering the spacecraft to various planetary swingbys with an accuracy varying from about five kilometers at Earth to 150 kilometers at Jupiter. The final approach to Saturn is predicted to have an accuracy of about 30 kilometers.

Huygens Probe Mission

Based on the primary launch opportunity, Cassini–Huygens will arrive at Saturn on July 1, 2004. On arrival, the Orbiter will make a close flyby and execute a Saturn orbit insertion

MAJOR MISSION MILESTONES
CASSINI–HUYGENS

Milestone	Date
Launch	10/06/1997
Venus 1 Swingby	04/21/1998
High-Gain Antenna Opportunity	12/16/1998 – 01/10/1999
Deep Space Maneuver	01/20/1999
Venus 2 Swingby	06/22/1999
Earth Swingby	08/17/1999
Asteroid Belt Crossing	12/12/1999 – 04/10/2000
High-Gain Antenna Earth-Pointing	02/01/2000
Jupiter Swingby	12/30/2000
Gravity Wave Experiment	11/26/2001 – 01/05/2002
Conjunction Experiment	06/06/2002 – 07/06/2002
Cruise Science On	07/02/2002
Gravity Wave Experiment	12/06/2002 – 01/15/2003
Phoebe Flyby	06/11/2004
Saturn Orbit Insertion	07/01/2004
Periapsis Raise	09/25/2004
Probe Separation	11/06/2004
Orbiter Deflection	11/08/2004
Probe Titan Entry	11/27/2004
Titan 1 Flyby	11/27/2004
Titan 2 Flyby	01/14/2005
Titan 3 Flyby	02/15/2005
Enceladus 1 Flyby	03/09/2005
Titan 4 Flyby	03/31/2005
Titan 5 Flyby	04/16/2005
Enceladus 2 Flyby	07/14/2005
Titan 6 Flyby	08/22/2005
Titan Flybys Continue	2005 – 2008
Mission Ends	07/01/2008

(SOI) propulsive maneuver to initiate a highly elliptical, 148-day orbit around the planet. This orbit will set up the geometry for the first encounter with Titan for the Huygens Probe mission, currently planned for November 27, 2004.

On November 6, 2004, approximately 22 days before the first Titan flyby, the Huygens Titan Probe will be released from the Orbiter. The Orbiter will turn to orient the Probe to its entry attitude, spin it up to about 7.29 revolutions per minute and release it with a separation velocity of about 0.33 meter per second. At least two navigational maneuvers will be performed before separation to ensure accurate targeting for atmospheric entry. Two days after separation, the Orbiter will perform an Orbiter deflection maneuver (ODM) to ensure that the Orbiter will not follow the Probe into Titan's atmosphere, and to establish the proper geometry for the Probe data relay link.

The Orbiter is targeted to similar aimpoint conditions at the second Titan flyby to permit a contingency Probe mission opportunity if anything prevents the Probe from being delivered on the first flyby.

Following completion of the predicted descent, the Orbiter will continue to listen to the Probe for 30 minutes, in the event the Probe transmissions continue after landing. The longest predicted descent time is 150 minutes.

When Probe data collection is completed, that data will be write-protected on each of the Orbiter's solid-state recorders. The spacecraft will then turn to view Titan with optical remote-sensing instruments, until about one hour after closest approach.

Soon after closest approach, the Orbiter will turn the high-gain antenna toward Earth and begin transmitting the recorded Probe data. The complete, four-fold redundant set of Probe data will be transmitted to Earth twice, and its receipt verified, before the write protection on that portion of the recorder is lifted by ground command — marking Probe mission completion.

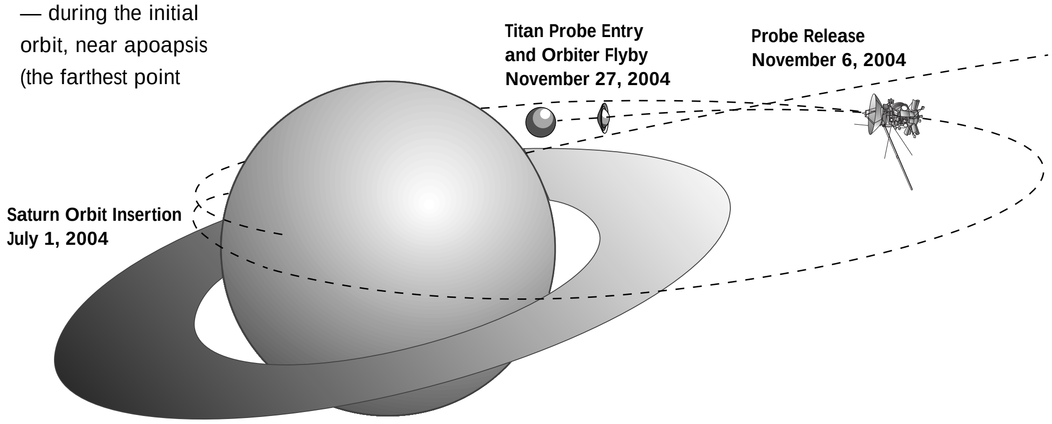
Saturn Orbiter Tour

The tour phase of the mission will begin at Probe mission completion and ends four years after the SOI. The reference tour described here, called Tour T18-3, consists of 74 orbits of Saturn with various orientations, orbital periods ranging from seven to 155 days and Saturn-centered periapsis radii ranging from about 2.6 to 15.8 R_S (Saturn radii).

Orbital inclinations with respect to Saturn's equator range from zero to 75 degrees, providing opportunities for ring imaging, magnetospheric coverage and radio (Earth), solar and stellar occultations of Saturn, Titan and the ring system.

JUST DROPPING BY

Shown here is the Cassini–Huygens flight path for the approach to Saturn, the Saturn orbit insertion maneuver, the initial Saturn orbit and the approach to the first Titan encounter. A propulsive maneuver — called the periapsis raise maneuver — during the initial orbit, near apoapsis (the farthest point from Saturn), raises periapsis (the nearest point to Saturn in the orbit) to correctly target the Orbiter for the first Titan flyby. If any problem arises with the Orbiter, Probe or ground system that prevents execution of the Probe mission at the first Titan flyby, mission controllers can decide to have the spacecraft fly by Titan without releasing the Probe, delaying the Probe's mission till the second Titan flyby on the second orbit of Saturn. The second Titan flyby is currently planned for January 14, 2005.

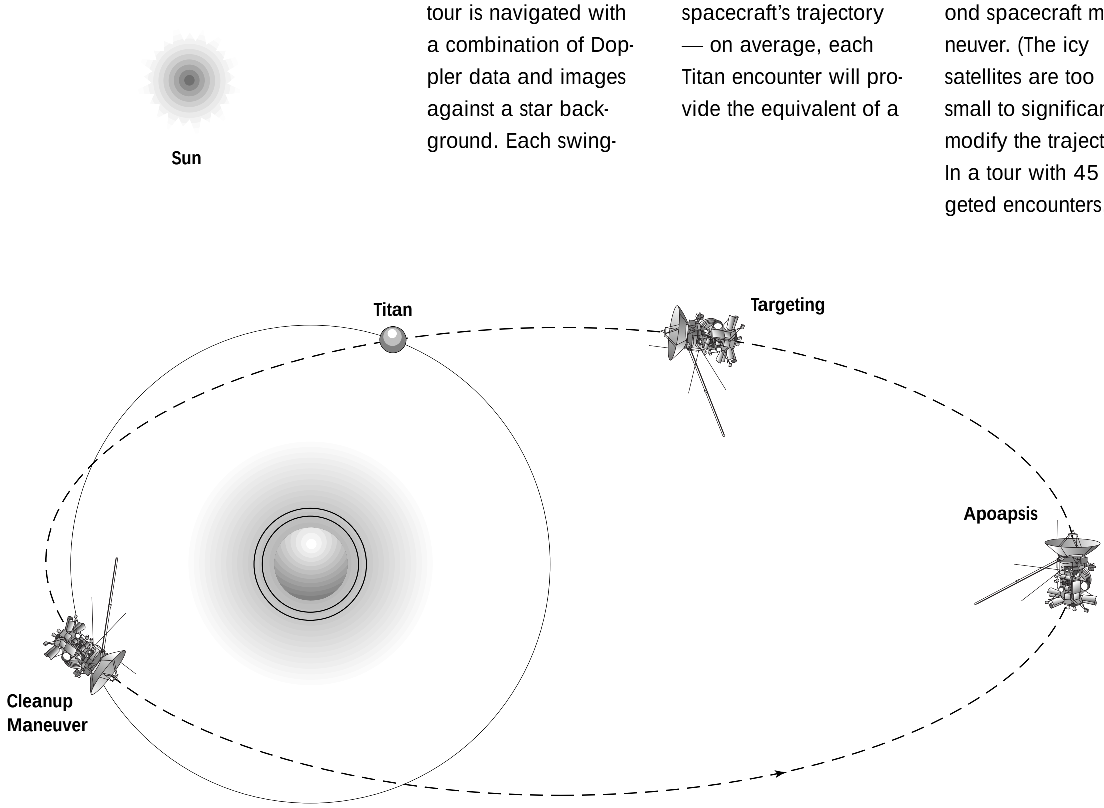


A total of 43 Titan flybys occur during the reference tour. Of these, 41 have flyby altitudes less than 2500 kilometers and two have flyby altitudes greater than 8000 kilometers. Titan flybys are used to control the spacecraft's orbit about Saturn as well as for Titan science acquisition. Our reference tour also contains seven close flybys of icy satellites and 27 additional distant flybys of icy satellites within 100,000 kilometers.

Close Titan flybys could make large changes in the Orbiter's trajectory. For example, a single close flyby of Titan can change the Orbiter's Saturn-relative velocity by hundreds of meters per second. For comparison, the total such change possible from the Orbiter's main engine and thrusters is about 500 meters per second for the entire tour. The limited amount of propellant available for tour operations is used only to provide small trajectory adjustments necessary to navigate the Orbiter, or to turn it in order to obtain science observations or to communicate with Earth.

Titan is the only satellite of Saturn massive enough to use for orbit control during a tour. The masses of the other satellites are so small that even close flybys (within several hundred kilometers) can change the Orbiter's trajectory only slightly. Consequently, Cassini tours consist mostly of Titan flybys. This places restrictions on how the tour must be designed. Each Titan flyby must place the Orbiter on a trajectory that leads back to Titan. The Orbiter cannot be targeted to a flyby of a satellite other than Titan unless the flyby lies almost along a return path to Titan. Otherwise, since the gravitational influence of the other satellites is so small, the Orbiter will not be able to return to Titan — and

STEERING BY THE STARS



The Cassini–Huygens tour is navigated with a combination of Doppler data and images against a star background. Each swing-by of Titan modifies the spacecraft's trajectory — on average, each Titan encounter will provide the equivalent of a 770-meters-per-second spacecraft maneuver. (The icy satellites are too small to significantly modify the trajectory.) In a tour with 45 targeted encounters, the spacecraft will perform about 135 maneuvers. Shown here is a three-maneuver sequence to control the trajectory from one Titan encounter to the next. The "cleanup" maneuver corrects for errors in the previous flyby. The sequence uses between eight and 11 meters per second, per encounter. The plan is to allow some variation in the actual Titan swing-by conditions that will reduce the amount of propellant required to accomplish the tour. The use of both radiometric and optical data results in a Titan delivery accuracy of 10 kilometers or less.

the tour cannot continue. Of course, the large number of Titan flybys will produce extensive coverage of Titan.

Tour Terminology

"Rev" numbers ranging from 1 to 74 are assigned to each tour orbit, assuming each orbit begins at apoapsis. The partial orbit from SOI to the first apoapsis is Rev 0. The rev number is incremented at each succeeding apoapsis. Two or more revs about Saturn may occur between successive Titan flybys; therefore, there is no correspondence between rev number and flyby number. Titan flybys are numbered consecutively, as are the targeted flybys of icy satellites. For example, the first flyby of Enceladus is Enceladus 1; the first of Rhea is Rhea 1.

"Orbit orientation" is the angle measured clockwise at Saturn from the Saturn–Sun line to the apoapsis. This is an important consideration for observations of Saturn's magnetosphere and atmosphere. The time available for observations of Saturn's lit side decreases as the orbit rotates toward the anti-Sun direction. Arrival conditions at Saturn fix the initial orientation at about 90 degrees. Due to the motion of Saturn around the Sun, the orbit orientation increases with time, at a rate of orientation of about one degree per month, which over the four-year tour results in a total rotation of about 48 degrees clockwise (as seen from above Saturn's north pole). Period-changing targeted flybys that rotate the line of apsides (orbital points nearest or farthest from the center of Saturn) may be used to add to or subtract from this drift in orbit orientation.

The "petal" plot on the facing page shows how targeted flybys combine with orbit drift to rotate the orbit from the initial orientation clockwise most of the way around Saturn to near the Sun line. In the coordinate system used in this diagram, the direction to the Sun is fixed. Encounters of satellites occur either inbound (before Saturn-centered periapsis) or outbound (after Saturn-centered periapsis).

A "targeted flyby" is one where the Orbiter's trajectory has been designed to pass through a specified aimpoint (latitude, longitude, altitude) at closest approach. At Titan, the aimpoint is selected to produce a desired change in the trajectory using the satellite's gravitational influence. At targeted flybys of icy satellites, the aimpoint is generally selected to optimize the opportunities for scientific observations, since the gravitational influence of those satellites is small. However, in some cases the satellite's gravitational influence is great enough to cause unacceptably large velocity-change penalties for a range of aimpoints, which makes it necessary to constrain the range of allowable aimpoints to avoid the penalty.

If the closest approach point during a flyby is far from the satellite, or if the satellite is small, the gravitational effect of the flyby can be small enough that the aimpoint at the flyby need not be tightly controlled. Such flybys are called "nontargeted." Flybys of Titan at distances greater than 25,000 kilometers — as well as flybys of satellites other than Titan at distances of greater than a few thousand kilometers — are considered nontargeted flybys.

Flybys of satellites other than Titan at distances up to a few thousand kilometers must be treated as targeted flybys to achieve science objectives, even though the satellite's gravitational influence is small. Opportunities to achieve nontargeted flybys of smaller satellites will occur frequently during the tour and are important for global imaging.

If the transfer angle between two flybys is 360 degrees (that is, the two flybys occur with the same satellite at the same place), the orbit connecting the two flybys is called a "resonant orbit." The period of a Titan-resonant orbit is an integer multiple of Titan's orbital period. The plane of the transfer orbit between any two flybys is formed by the position vectors of the flybys from Saturn.

If the transfer angle is either 360 degrees (that is, the two flybys occur with the same satellite at the same place) or 180 degrees, an infinite number of orbital planes connects the flybys. In this case, the plane of the transfer orbit can be inclined significantly to the planet's equator. Any inclination can be chosen for the transfer orbit, as long as sufficient bending is available from the flyby to get to that inclination. If a spacecraft's orbital plane is significantly inclined to the equator, the transfer angle between any two flybys forming this orbital plane must be nearly 180 or 360 degrees.

If the angle between the position vectors is other than 180 or 360 degrees — as is usually the case — the orbital plane formed by the position vectors of the two flybys is unique and lies close to the satellites' orbital planes (except for Iapetus), which are close to Saturn's equator. In this case, the orbit is "nonresonant." Nonresonant orbits have orbital periods that are not integer multiples of Titan's period. Nonresonant Titan–Titan transfer orbits connect inbound Titan flybys to outbound Titan flybys, or vice versa.

General Tour Strategy

This section contains specific descriptions of the segments in the reference tour T18-3.

Titan 1–Titan 2. The first three Titan flybys reduce orbital period and inclination. The Orbiter's inclination is reduced to near zero with respect to Saturn's equator only after the third flyby; so, these three flybys must all take place at the same place in Titan's orbit. The period-reducing flybys were designed to be inbound, rather than outbound, to accomplish the additional goal of rotating the line of apsides counterclockwise. This moves the apoapsis toward the Sun line in order to provide time for observations of Saturn's atmosphere, and to allow Saturn occultations on subsequent orbits to occur at distances closer to Saturn.

Titan 3. After the inclination has been reduced to near Saturn's equator, a targeted inbound flyby of Enceladus is achieved on the fourth orbit on the way to an outbound flyby of Titan on orbit five on March 31, 2005. Changing from an inbound to an outbound Titan flyby here orients the line of nodes nearly normal to the Earth line. This minimizes the inclination required to achieve an occultation of Saturn, preparing for the series of near-equatorial Saturn and ring occultations that follows.

A Titan flyby occurring normal to the Earth line can be inbound or outbound (like any Titan flyby). For Titan flybys occurring nearly over the dawn terminator as in the reference tour, the spacecraft is closer to Saturn during the occultation if the Titan flyby is outbound than if it is inbound. The science return from the occultation is much greater if the spacecraft is close to Saturn than if it is far away.

In particular, the antenna "footprint" projected on the rings is smaller when the occultation occurs closer to Saturn, improving the spatial resolution of the "scattered" radio signal observations. This is an important influence on the design of the tour. Lowering inclination to the equator, switching from inbound to outbound Titan flybys and rotating the orbit counterclockwise near the start of the tour all help keep the spacecraft close to Saturn during the subsequent series of equatorial occultations.

Titan 4–Titan 7. Here, the minimum inclination required to achieve equatorial occultations is about 22 degrees. The two outbound flybys on March 31 and April 16, 2005, in-

MAIN CHARACTERISTICS OF TOUR SEGMENTS

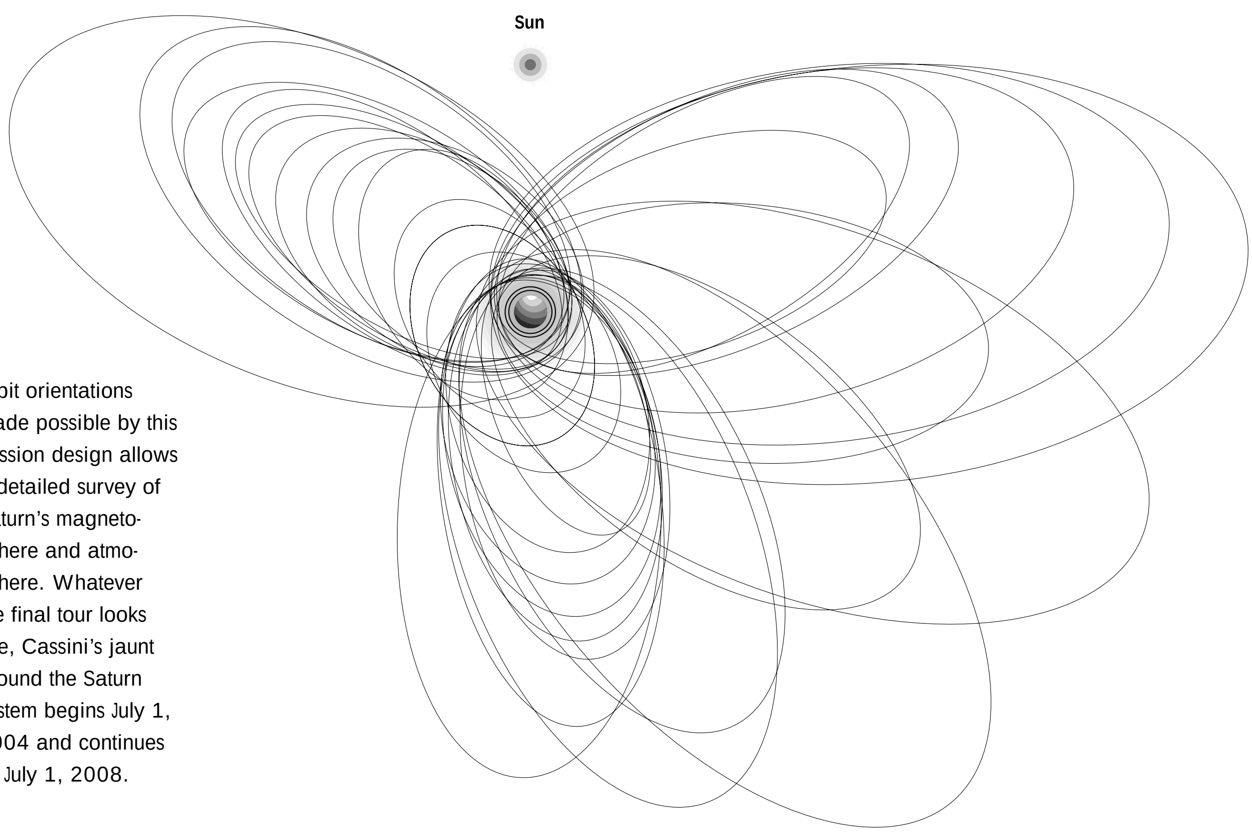
Titan Flyby	Comments
T1–T2	Reduce period and inclination, target for Probe mission.
T3	Rotate counterclockwise and transfer from inbound to outbound.
T4–T7	Raise inclination for eight equatorial Saturn–ring occultations and lower again to equator.
T8–T15	Rotate clockwise toward anti-Sun direction.
T16	Increase inclination and rotate for magnetotail passage.
T17–T31	180-degree transfer sequence (including several revolutions for ring observations).
T32–T34	Target to close icy satellite flybys of Enceladus, Rhea, Dione and Iapetus.
T35–T43	Increase inclination to 71 degrees (maximum value in tour).

crease inclination to this value. The second of these also changes the period to 18.2 days. At this period, seven orbiter revolutions and eight Titan revolutions are completed before the next Titan flyby, producing seven near-equatorial occultations of Earth by Saturn (one on each orbit). On all eight of these revolutions, the Orbiter crosses Saturn's equator near Enceladus' orbit; on the fourth revolution, the second targeted flyby of Enceladus occurs. Enceladus' gravity is too weak to displace inclination significantly from the value required to achieve occultations. The Titan flybys on August 22 and September 7, 2005, reduce inclination once again to near Saturn's equator.

Titan 8–Titan 15. After inclination is reduced and the spacecraft's orbital plane again lies near Saturn's equator, a series of alternating outbound / period-reducing and inbound / period-increasing flybys — lasting about 10 months — is used to rotate the orbit clockwise toward the magnetotail. The first flyby in this series occurs on September 26, 2005, and the last occurs on June 1, 2006.

Titan 16. After rotating the orbit to place apoapsis near the anti-Sun line, inclination is raised to about 10 degrees with one flyby on July 6, 2006, to achieve passage through the current sheet in the magnetotail region. At distances this far from Saturn, the current sheet is assumed to be swept away from Saturn's equatorial plane by the solar wind. After this flyby, apoapsis distance is about 49 R_S, exceeding the 40 R_S magnetospheric and plasma science requirement associated with magnetotail passage. Besides providing a magnetotail passage, this inclination-raising flyby is the first of a sequence of flybys that makes up the 180-degree transfer sequence described next.

ON A FOUR-YEAR TOUR



This view from above Saturn's north pole shows all possible orbits in a rotating coordinate system, in which the Sun direction is fixed, for a possible Saturn system tour referred to by mission designers as "Tour T18-3." This type of diagram is often referred to as a "petal" plot due to its resemblance to the petals of a flower. The broad range of orbit orientations made possible by this mission design allows a detailed survey of Saturn's magnetosphere and atmosphere. Whatever the final tour looks like, Cassini's jaunt around the Saturn system begins July 1, 2004 and continues till July 1, 2008.

Titan 17–Titan 31. This series of flybys completes a 180-degree transfer sequence. The first several flybys of this sequence — all inbound — are used to raise inclination as quickly as possible using the minimum altitude of 950 kilometers at each flyby. The Titan flyby of August 22, 2006, reduces the period to 16 days, as well as raising inclination. The period is then kept constant at 16 days as inclination is raised, except during an interval of 48 days between flybys on October 25 and December 12, 2006. The flyby on October 25, 2006, reduces the period to 12 days (a resonance of three Titan revs for every four spacecraft revs) in order to provide extra spacecraft revs between Titan flybys for observing the rings, for which the geometry is particularly favorable at this point in the tour. The flyby on December 12, 2006, increases the period back to 16 days.

As inclination is raised, the periapsis radius increases and apoapsis radius decreases until the orbit is nearly circularized at an inclination of about 60 degrees. The Orbiter's trajectory then crosses Titan's orbit at not one, but two points (the ascending and descending nodes), making possible a 180-degree transfer from an inbound Titan flyby to an outbound Titan flyby. After this 180-degree transfer is accomplished, the next seven Titan flybys, all of which are outbound, reduce inclination as quickly as possible to near Saturn's equator. This 180-degree transfer flyby sequence (raising inclination, accomplishing the 180-degree transfer, then lowering inclination again) rotates the line of apsides about 120 degrees so that apoapsis lies between the Sun line and Saturn's dusk terminator.

Titan 32–Titan 34. The flybys immediately following the completion of the 180-degree transfer sequence and the return of the spacecraft's orbital plane to near Saturn's equator are used to target flybys of Enceladus, Rhea, Dione and Iapetus. The Enceladus and Rhea flybys occur on successive orbits (46 and 47) between the Titan flybys on May 28 and July 18, 2007. The Titan flyby on September 1, 2007, raises inclination to seven degrees to target to Iapetus.

Titan 35–Titan 43. Following the Iapetus flyby on September 18, 2007, the Orbiter is targeted to an outbound Titan flyby on October 3, 2007, which places the line of nodes close to the Sun line. Starting with this flyby, the rest of the tour is devoted to a "maximum-inclination sequence" of flybys designed to raise inclination as high as possible for ring observations and in situ fields and particles measurements (in this case, to about 75 degrees). In this reference tour, the orbits during this maximum-inclination flyby sequence are oriented nearly toward the Sun, opposite the magnetotail, to ensure several occultations of Earth by Saturn and the rings at close range.

During this flyby sequence, first, orbit "cranking" and then, orbit "pumping" (after a moderate inclination has been achieved) are used to increase inclination, eventually reducing the orbit period to just over seven days (nine Orbiter revolutions, four Titan revolutions). The closest approach altitudes during this sequence are kept at the minimum allowed value to maximize gravitational assist at each flyby.

End of Mission

The reference tour ends on July 1, 2008, four years after insertion into orbit about Saturn, 33.5 days and four and a half spacecraft revs after the last Titan flyby (which occurs on May 28, 2008). The spacecraft's orbital period is 7.1 days (a resonance of four Titan revs to nine spacecraft revs), its inclination is 71.1 degrees and its periapsis radius is four R_S.

The aimpoint at the last flyby is chosen to target the orbiter to a Titan flyby on July 31, 2008 (64 days after the last flyby in the tour), providing the opportunity to proceed with more flybys during an extended mission, if resources allow. Nothing in the design of the tour precludes an extended mission.